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Carbon nanotube electron field emitters for X-ray imaging of human breast cancer

Emily Gidcumb[1], **Bo Gao**[2,4], **Jing Shan**[3], **Christy Inscoe**[1,3], **Jianping Lu**[1,3], and **Otto Zhou**[1,3]

Emily Gidcumb: edmorgan@email.unc.edu; Otto Zhou: zhou@email.unc.edu

[1]Department of Applied Physical Sciences, University of North Carolina, Chapel Hill, NC 27599-3287

[2]Xintek Inc., 7020 Kit Creek Road, Suite 200, Research Triangle Park, NC 27709

[3]Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255

Abstract

For imaging human breast cancer, digital breast tomosynthesis (DBT) has been shown to improve image quality and breast cancer detection in comparison to 2D mammography. Current DBT systems have limited spatial resolution and lengthy scan times. Stationary digital breast tomosynthesis (s-DBT), utilizing an array of carbon nanotube (CNT) field emission X-ray sources, provides increased spatial resolution and potentially faster imaging than current DBT systems. This study presents the results of detailed evaluations of CNT cathodes for X-ray breast imaging tasks. The following were investigated: high current, long-term stability of CNT cathodes for DBT; feasibility of using CNT cathodes to perform a 2D radiograph function; and cathode performance through several years of imaging. Results show that a breast tomosynthesis system using CNT cathodes could run far beyond the experimentally tested lifetime of one to two years. CNT cathodes were found capable of producing higher currents than typical DBT would require, indicating that the s-DBT imaging time can be further reduced. The feasibility of using a single cathode of the s-DBT tube to perform 2D mammography in 4 seconds, was demonstrated. Over the lifetime of the prototype s-DBT system, it was found that both cathode performance and transmission rate were stable and consistent.

1. Introduction

Apart from skin cancers, breast cancer is the most prevalent type of cancer in women [1]. Digital mammography is currently the gold standard for the early detection of breast cancer. However, the limitations of digital mammography have been well documented. Digital mammography is known to have high false positive and high false negative rates. It is a two-dimensional (2D) imaging technique which can make distinguishing tumour from overlying tissue difficult. Digital breast tomosynthesis (DBT) was developed to mitigate some of the limitations of 2D digital mammography. DBT is a limited-view computed tomography technique that yields reconstructed planes through the imaged breast volume. The

[4]Current address: XinRay Systems, 7020 Kit Creek Road, Suite 210, Research Triangle Park, NC 27709

reconstructions are formed from a series of projection images taken at different angles [2, 3]. As a quasi-three-dimensional (3D) imaging modality, it has the potential to improve conspicuity of cancerous structures by removing the visual clutter associated with normal breast anatomical features. The performance of current DBT systems is partially limited by conventional X-ray tube technology, in which X-rays are emitted from a single focal point. As a whole, DBT systems suffer from relatively low spatial resolution and long scanning time [4-6]. This is particularly problematic because the scanners have a low sensitivity for microcalcifications (MCs), a hallmark of breast cancer [7]. In the current DBT systems, projection images are collected by moving an X-ray tube, mounted on a rotating gantry, around the compressed breast. Motion of the X-ray source during exposure degrades the image quality, limits the scanning speed, and restricts the angular coverage. Long scan times result in additional image degradation due to patient motion, and in increased patient discomfort from breast compression [6].

To overcome the limitations of the current rotating-gantry DBT technology, a stationary DBT (s-DBT) system has been successfully developed [8-10] utilizing an array of carbon nanotube (CNT) field emission X-ray sources [11]. A photo of a prototype s-DBT system is shown figure 1B. To acquire projection images from different angles, individual X-ray sources in the s-DBT tube are electronically activated. No mechanical motion of the source, detector, or patient is required. An example reconstructed image of a breast lumpectomy specimen is shown in figure 1C, where the chosen reconstruction plane shows the lesion spiculations in focus. Higher spatial resolution is achieved by completely removing the image blur due focal spot motion. When coupled with a fast flat panel detector, this system has the potential to reduce total imaging time; benefiting the patient while reducing image blur from their motion. Preliminary studies show an improvement in spatial resolution in comparison with rotating-gantry DBT systems [10, 12]. The s-DBT technology is currently being evaluated by an Institutional Review Board-approved patient trial at N.C. Cancer Hospital[5] (Chapel Hill, NC); a photograph of the system to be used is shown in figure 1B.

The performance of the CNT field emission cathodes forms the foundation of this novel imaging device. To translate this technology into a viable clinical device, the CNT field emitters need to meet several requirements: short imaging time, achieved through high current and high current density; stable operation at high anode voltage and power; long system lifetime; and consistency amongst cathodes. In a conventional thermionic X-ray source, the tube current is primarily limited by the elevated anode temperature reached during exposure, which can rise above 2,000 °C [13]. For the CNT field emission X-ray tube, the anode temperature limit remains the same. In the present design, the anode is stationary and does not dissipate heat through rotation. The issues of emission current and stability, important not only for X-ray generation but also for other vacuum electronic applications [14], need to be investigated using protocols relevant to the specific operational conditions for a certain application. The performance of the CNT emitters are known to depend on operating conditions such as the vacuum level, total cathode current, pulse width,

[5]U.S. National Library of Medicine. (January 2013). Comparison of Stationary Breast Tomosynthesis and 2-D Digital Mammography in Patients With Known Breast Lesions. *ClinicalTrials.gov*. Retrieved November 4, 2013. From clinicaltrials.gov/ct2/show/NCT01773850.

duty cycle, etc. The majority of the field emission research over the years has been focused on field-emission flat panel displays, which have significantly lower power requirements than X-ray tubes [15]. Currently, there are no clear conclusions among the limited number of publications on the high power performance of CNT emitters. This is mainly due to wide variations in CNT cathode quality and experimental conditions used in these studies [16-20].

The purpose of this study is to systematically investigate the field emission performance of the CNT cathode in the context of breast imaging. In particular, the following issues are investigated: the maximum, stable emission current and current density that CNT cathodes can produce; the ability of a single CNT cathode to quickly deliver the X-ray output required for a 2D mammogram; and the long-term stability of the CNT cathodes.

The motivation behind these goals comes from the desire to shorten s-DBT imaging time and to expand the clinical potential of the s-DBT technology to include 2D mammography, if it would be needed. As previously mentioned, conventional DBT systems use rotating gantries for their X-ray tubes. In order to shorten scan time enough to prevent blurring from patient motion on a rotating gantry system the gantry rotation speed must increase. However, increasing gantry rotation speed increases image blur due to X-ray source motion. In contrast, there is no mechanical motion during imaging in an s-DBT system. Therefore, shortening s-DBT imaging time will effectively minimize image blur due to patient motion, and will reduce patient discomfort from compression. It has been shown that reducing a DBT scan time to 2 seconds essentially eliminates the effect of patient motion blur on images [6]. In order to shorten imaging time, higher emission current will be required by each cathode, and in a shorter pulse length. In context to the motivation for a 2D mammography capability, clinical applications for such a function could include image-guided needle breast biopsy, image-guided needle localization, or aiding patient diagnosis according to specific radiologists' preference. The challenge in the case of 2D imaging is that the imaging dose, which is distributed among many cathodes in the case of tomosynthesis, must be drawn from a single cathode.

2. Experiment

The CNT cathodes were fabricated by electrophoretic deposition of a composite film of pre-formed CNTs and inorganic binders on a conducting substrate, followed by heat treatment [21]. The general morphology of the CNT cathode can be observed through SEM, an example image is shown in figure 2A. Small-diameter, multi-walled carbon nanotubes synthesized by the chemical vapour deposition method were used as the starting material [22]. The diameter of the nanotubes ranges from 2 – 8 nm, and the nanotube lengths range from 2 – 6 μm. The defect density of the CNT samples deposited on the cathodes is relatively low with an I_D / I_G ratio between 0.2 – 0.3. An example of Raman spectroscopy data for these CNTs is shown in figure 2B. The gate electrode is comprised of a series of tungsten mesh welded onto a metal gate frame. The gate electrode is grounded, and negative voltage is applied to the cathode. The field emission properties of the CNT cathodes were evaluated using a testing vacuum chamber housing 3 X-ray sources. The sources are similar in structure as those in the s-DBT X-ray tube, each consisting of: a CNT cathode, an extraction gate electrode, an Einzel-type series of electrostatic focusing lenses [9, 19], and a tungsten anode.

Accelerated lifetime measurements were performed by pulsing the cathodes using various pulse widths and duty cycles, which will be discussed in more detail. The tests were performed with the base vacuum pressure, the pressure when the electron beam is off, in the 10^{-8} – 10^{-9} torr range. The peak pressure during the emission pulses was maintained below 1x10-6 torr. A schematic of the experimental set up is shown in figure 3.

Different measurements were performed to meet the previously stated goals: reaching the maximum, stable emission current and current density for tomosynthesis imaging; using a single CNT cathode to quickly deliver the anode exposure required for a 2D mammogram; and, measuring the long-term stability of the CNT cathodes.

2.1 Maximum, stable current for tomosynthesis

In the mammography clinic, the imaging dose for breast cancer screening varies from patient to patient. On average, a tomosynthesis scan, for breast thicknesses ranging 10 – 110 mm, requires around 50 –100 mAs total anode exposure [23]. Anode exposure is defined as anode current in milliamperes multiplied by the pulse length, or exposure time, in seconds. An s-DBT system exposure of 100 mAs is approximately equivalent to delivering 700 mR, or 6 mGy, entrance dose at the breast surface [12]. The dose is evenly distributed among the set of sources used, typically 15 sources over a 28 degree angular span. For a 15-view, 100 mAs imaging protocol, each source produces 6.67 mAs on the anode [10].

A series of tests were carried out to determine the upper limit of the emission current from a CNT cathode within the context of tomosynthesis imaging. The cathode had a deposition area of dimensions 2.5 mm × 13.0 mm; known to produce an average focal spot size of 0.6 mm × 0.6 mm at FWHM [10]. Lifetime measurements were carried out in pulse mode at a frequency of 0.1 Hz with both 250 ms and 125 ms pulses, giving duty cycles of 2.5% and 1.25%, respectively. Two cathodes were used in these measurements. The first was used for all 250 ms testing, which was performed sequentially. The second cathode was used for the 125 ms testing.

The intention of these measurements was to determine the intrinsic current limitation of the CNT cathodes. Maximum current output determines how fast the necessary X-ray dose can be delivered to a patient. Higher current allows imaging time to decrease, while maintaining the same anode exposure, which is directly related to X-ray dose. Shorter imaging time benefits the patient by decreasing time under compression and improving image quality. For example, if the tube current, defined as the current reaching the anode, is 27 mA, then a 250 ms exposure is needed, per view, to obtain an anode exposure of 6.67 mAs. The exposure time can be reduced to 125 ms if the tube current is increased to 54 mA.

2.2 Testing the requirements for a 2D mammogram

Here the feasibility of a single CNT cathode to deliver the dose needed for a typical 2D image was evaluated. Clinically, a single mammogram exposure, of which there are usually four to six in a complete imaging session, requires anywhere from 9 – 107 mAs, depending on the patient [23]. For this purpose, the stability of the CNT cathode was measured for delivering pulses with an exposure of either 50 mAs or 75 mAs, which is in the middle of the range of typical clinical use. In addition, pulse width must be considered because short exposure times are desired to minimize motion blurring. However, for an initial feasibility test of using CNT cathodes for this purpose, a 4 s pulse width was tested.

Feasibility testing was completed on a single cathode of equal size to the cathodes used in the tomosynthesis accelerated lifetime tests. As in the lifetime tests, these experiments were also completed sequentially on a single cathode. Data was taken over a range of anode voltages, 10 – 35 kV. Anode current was only measured up to 20 kV due to the voltage limitations of the current probe. Using these measurements, a transmission rate was calculated and used to determine the anode current at higher anode voltages. The current probe used was a Tektronix TCP312A with the TCPA300 Current Probe Amplifier (Tektronix, Beaverton, OR 97707).

Transmission rate is defined as the percentage of cathode current that reaches the anode. Figure 3 includes an illustration of the electrode structure for each cathode – anode pair, with a simulated electron beam trajectory shown passing through the electrodes. After electrons are produced from the CNTs, they pass through three electrodes before reaching the anode: gate, 1st focus, and 2nd focus. Upon reaching each electrode, some of the original cathode current is lost. Therefore, only a portion of the created cathode current reaches the anode to produce X-rays. Anode current is defined as the remaining cathode current that reached the anode, and can be estimated if the cathode current and transmission rate are known.

2.3 Long-term stability

Long-term stability of the CNT cathodes was measured by analyzing the prototype s-DBT systems' cathode voltage increases over a two-year timespan. Increases in the cathode voltage required to extract the same magnitude of current indicates that the cathode experienced degradation. Typically, all cathodes used in the s-DBT tube, having the same deposition area of the other cathodes tested in this study, were run at around 40 mA of cathode current. Therefore, the cathode voltages required to produce 39 ± 1 mA of current were recorded over time. This was done for all 31 CNT cathodes over a two-year period, during which the device was heavily used for tomosynthesis imaging and characterization, with the cathodes assigned even numbers having been used most.

In addition to cathode voltage increases, transmission rate measurements were made over time. This was done to verify the overall stability of tube performance. The measurements were taken with both focusing electrodes grounded, which minimizes current loss to the focusing electrodes. Also, most imaging with the s-DBT system is done with the focusing electrodes grounded, so this measurement reflects the transmission rate available during typical imaging. The time points for these measurements are September of 2011 and June of 2013. The 2011 data had an anode voltage of 15 kV, 35 mA cathode current, and 295 ms pulse widths. The 2013 data had an anode voltage of 30 kV, two cathode current settings of 10 mA and 40 mA, and 250 ms pulse widths.

3. Results and Discussion

3.1 Maximum, stable current for tomosynthesis

Figure 4 shows the field emission testing results for the following settings: 250 ms at 27 mA, 41 mA, 60 mA, and 80 mA cathode current; corresponding to current densities of 83.1 mA/cm^2, 126 mA/cm^2, 185 mA/cm^2, and 246 mA/cm^2. In addition, there was 125 ms testing at 78 mA, corresponding to a current density of 240 mA/cm^2. All 250 ms testing was done sequentially on one cathode, and the 125 ms testing done on a separate cathode. According to plots 4A through 4C, the cathode showed stable behaviour at 27 mA, 41 mA, and 60 mA conditions. The percentage change in electric field per 1,000 pulses for these current settings were 0.017%, 0.054%, and 0.159%, respectively. The 41 mA conditions are most similar to the imaging conditions used in the s-DBT system. These results indicate that at conditions typical of tomosynthesis imaging, the CNT cathodes could operate stably far beyond the length of these experiments. It can be seen that in some parts of figure 4 that although cathode current was held constant there are some local fluctuations in the current data. This is likely the result of using a larger-than-necessary compensating voltage step in the control programs' feedback loop.

In figure 4A, the trend of the electric field appears to be decreasing over time. However, the reported percentage change is positive 0.017% per 1,000 pulses. This is due to the fact that the target cathode current, 27 mA, was reached during a time of increasing electric field. For approximately 300 pulses the electric field continued to rise after reaching 27 mA. The electric field peaked and then decreased over the majority of the experiment. The electric field value at the end of the 27 mA testing, although having decreased over time, did not fall below the initial electric field value at the beginning of the experiment. This explains how the electric field was found to increase, although it appears to primarily decrease over the course of the experiment.

Although 60 mA was stable, the cathode did suffer higher rates of degradation. However, the higher rate of degradation could be impacted by the fact that all settings were tested sequentially on one cathode. To achieve the necessary anode exposure for a tomosynthesis scan, 60 mA in 250 ms is more than is required. A typical tomosynthesis scan requires 100 mAs of anode exposure. Assuming a 60% transmission rate for 30 kVp anode voltage, a series of 15 projections using 60 mA, 250 ms cathode pulses would produce 135 mAs. To achieve a 100 mAs exposure over 15 projections, a 60 mA pulse would only need to be 185 ms in duration. Data supporting the assumption of a 60% transmission rate is presented in section 3.3 of this paper.

Figures 4D and 4E highlight the effect of pulse width on CNT cathode degradation. The 80 mA, 250 ms test indicated significant cathode degradation by the rapid decrease in cathode current, within a fraction of the time over which the other settings were tested. There was an 8.7% degradation in only 2,561 pulses, giving a change in electric field per 1,000 pulses of 3.4%. The rapid decrease in cathode current that followed indicates catastrophic emitter failures. After this degradation occurred, the cathode current could only be maintained at approximately 40 mA, due to the voltage limit on the cathode power supply and the damage suffered by the cathode. In contrast, the 78 mA, 125 ms setting fared much better over a much longer testing period, noting again that this testing was done on a separate cathode. In over 85,000 pulses there was only a 17.8% degradation. When normalized to percent change in electric field per 1,000 pulses, the degradation was only 0.207%. The cathode current for 78 mA, 125 ms was stable, and lasted for a duration approximately 34 times longer than the 80 mA, 250 ms setting.

Table 1 shows a summary of the results for all tested conditions. Columns 1 and 2 state the current value and pulse width of each setting, respectively. The number of pulses tested, in column 3, is the number of pulses between the first and last pulse at which the current reached ± 2.5% of the stated current value from column 1. The length of accelerated lifetime tested in years was calculated by assuming a 260 day work-year in which an average of 30 or 60 patients would receive an average of four images each day. In most clinical settings, 60 patients per day would be an extreme case, whereas 30 patients per day would be closer to average. In this context, each pulse tested is equivalent to one projection image that an individual cathode would produce during each image taken. The term accelerated lifetime implies that the number of images a cathode could produce was tested back-to-back, instead of through the course of actual clinical use. The accelerated lifetime length reported here is not the maximum lifetime possible, just the portion of the lifetime tested. The percent change in electric field is the difference in electric field between the first and last pulse, relative to the electric field of the initial pulse, and normalized per 1,000 pulses.

Decreasing the pulse width, while maintaining the same current, decreases the heat produced due to electron bombardment with the gate material. Because the gate is so close to the cathode, the lower temperature environment will allow the cathode to run stably for a much longer period of time. In addition, it is known that Joule heating of nanotubes at high emission currents can lead to nanotube degradation [24, 25]. It is unknown which heating effects are predominant in impacting cathode lifetime in this case. Decreasing the pulse width benefits imaging applications because it is directly related to decreasing imaging time, important for maintaining high image quality. The major factors impacting imaging time are the length of the X-ray pulses and the readout time of the X-ray detector. The readout time of the detector is the amount of time the detector takes per projection to read out the information it has acquired during a particular exposure. The readout time of the current Hologic Selenia Dimensions detector, for binned mode, is 180 ms [12]. Using 15 projections for a complete tomosynthesis image set, 250 ms pulses would make imaging time 6.45 seconds long. If instead, the pulse width could be decreased to 125 ms by using a higher cathode current, imaging time would be lowered to 4.58 seconds. Assuming a 60% transmission rate, the 78 mA, 125 ms setting could produce 87.75 mAs in 4.58 seconds. To produce 100 mAs at 78 mA would require 142 ms pulses resulting in an imaging time of 4.83 seconds using the current detector. This time would also decrease using an X-ray detector with a faster readout time. If the detector readout was reduced by half, to 90 ms, a 15 projection image set could be acquired in 5.10 seconds with 250 ms pulses and in 3.48 seconds with 142 ms pulses.

3.2 Testing the requirements for a 2D mammogram

These results measure the feasibility of the CNT cathodes' ability to output the current levels required to perform a 2D mammography image. A 2D image requires much more dose than an individual projection of a tomosynthesis image set. This task was tested using much longer pulse widths as an initial feasibility measure, but using long pulse widths is not a requirement for 2D mammography in general. Before the feasibility testing began, an initial source characterization was done with use of an I-V curve, plotted in figure 5A. The turn-on field measured for this cathode was less than 2.6 V/μm, defining the turn-on field as that needed to produce 10^{-6} A/cm^2. The I-V curve reached a maximum current of 38.8 mA and a current density of 119 mA/cm^2, which was more than enough for the testing requirements here. The 4 s pulse width testing results in figure 5 reveal that the CNT cathodes can produce enough current to create an anode exposure equivalent to that typically used in 2D mammography imaging.

There were two exposure targets for the 4 s pulse width testing, 50 mAs and 75. The field emission testing was done consecutively on the same cathode, as can be seen in figures 5B and 5C. The results are plotted versus pulse number, with each pulse being 4 seconds in length, an example of which is plotted in the inset of figure 5C. The anode exposure was calculated by multiplying the pulse width by the anode current. Anode current was directly measured for anode voltages ranging from 10 – 20 kV. An average transmission rate of 55.4 ± 0.4% was calculated for pulses with an estimated anode exposure within 50.0 ± 2.5 mAs. For the data taken at 25 – 35 kV anode voltage, this transmission rate was used to estimate the anode current. Pulse number 80 in figure 5B marks the beginning of the 25 kV and above data.

Pulses were considered to meet the target anode exposure if the calculated value was within 5% of the target value. For 50 mAs this meant pulses valuing 50.00 ± 2.50 mAs, and for 75 mAs it meant 75.00 ± 3.75 mAs. The cathode current pulses reaching the 50 mAs target averaged 23.2 ± 0.5 mA, giving an average current density of 71.4 mA/cm^2. The average current for the target pulses in the 75 mAs experiment was 33.5 ± 0.4 mA, corresponding to an average density of 103.1 mA/cm^2.

This feasibility test produced 73 pulses within 5% of the target anode exposure of 50 mAs, and 58 pulses within 5% of 75 mAs. Since this was a feasibility measure, not a lifetime measure, there is not prediction of how long these settings could be maintained. However, there was no intimation at the end of the experiment that many more pulses could not be completed, indicated by the sustained applied electric field. The slow rate of increases in the applied electric field can be seen in figures 5B and 5C.

3.3 Long-term stability

This section presents the data collected on the s-DBT prototype system during its use in the laboratory over a period of three years. These measures illustrate the reliability of the system over time. The cathodes were shown to have low rates of degradation, and consistent transmission rates over time. Figure 6 plots the measured cathode voltage required to emit 39 mA of cathode current from each cathode in the prototype s-DBT system, 31 in total. The measurements were done at two time points. The first was December of 2010 and the second was November of 2012, giving almost two years' time between when these measurements were taken. During that time, the system was used heavily for imaging, but not all beams were necessarily fired for each use.

As expected, almost every beam shows an increase in the cathode voltage required to emit 39 mA of current over the two-year time period. This increase is due to the degradation of the cathodes whereby the best CNT emitters are lost over time. To utilize the other emitters requires an increasingly strong electric field to be applied.

The original data, taken in December of 2010, averaged 1,400 V applied between the cathode and the gate for all 31 cathodes, with a standard deviation of 130 V. Two years later, the average voltage to create 39 mA was 1,800 V, with a standard deviation of 120 V. It is important to note that the measurements were made using a multi-pixel electronic control system in the learning mode, which uses 250 μs pulses. Typical operation uses 250 ms pulses, and from experience there is a ±10 V discrepancy between learning curve values and operating values.

Cathode 30 showed a decrease of approximately 45 ± 8 V in the cathode voltage required to produce 39 mA of current. This indicates that either this cathode, under relatively heavy use, did not degrade as the others did, or even improved. It is unlikely that the cathode did improve over such a long time period; it is more likely an error occurred during the measurement of the initial cathode voltage.

The s-DBT tube is equipped with 31 cathodes, but in general, imaging protocols only call for groups of 15 beams to be used. The two groups generally used are the even numbered beams and the odd numbered beams. The numbering of the beams follows those used in the x-axis of figure 6, where the odd numbers make up the odd beam group, and the same for the even beam group. Evaluating the degradation of even beams versus odd beams shows a similar average percent increase from the original voltage. On average, even beams' percentage increase relative to the original voltage was 36% with a standard deviation of 21%. Odd beams increased, on average, 34% with a standard deviation of 19%. Even though the odd beams were used less regularly, their degradation matched pace with the more heavily used even beams. This indicates that cathodes undergo some passive degradation from being in a chamber with other cathodes due to increased ion bombardment during the momentary pressure increases during neighbouring cathodes' field emission pulses. This is supported by general experience in the laboratory as well.

Figure 7 and table 2 show the results of the transmission rate measurements of the s-DBT tube over time. Figure 7 plots the transmission rate for each of the 31 cathodes inside the X-ray tube at two different time points. The earliest time point here is about 10 months after the initial time point of the cathode voltage measurements presented in figure 6. The data taken on September 2011 included each of the cathodes. The data from June 2013 is only for the cathodes given even number identifiers.

Table 2 gives all of the settings used for each measurement including anode voltage and pulse width. The reported average transmission rate and standard deviation for all beams

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measured in that data set; 15 for the earliest date, and 31 for the later date. In 2011, the average transmission rate for all cathodes was 61%, and in 2013 it was 67% and 63% for the 10 mA and 40 mA data, respectively. The average transmission rate over time is unchanged taking into account the standard deviation of the data sets, equal to 4%. The 10 mA data is barely within the average range of the higher current settings, implying a higher transmission rate is available at lower currents.

4. Conclusions

This paper presents results that illustrate the robustness of carbon nanotube cathodes for the application of imaging breast cancer. Typical operation of the s-DBT system is closest to the 41 mA, 250 ms experimental setting. The normalized degradation for the 41 mA, 250 ms pulse testing was 0.054% over a period of time equal to one and one-third years of actual use. This low degradation rate indicates that actual cathode lifetime at this setting would be considerably longer. It was also shown that CNT cathodes can stably perform a tomosynthesis imaging task at higher currents. The experimental setting of 78 mA with 125 ms pulses was tested for an equivalent of two and three-quarters years with a 0.207% normalized increase in electric field. The results indicate that the cathode would continue to perform stably for much longer than the length of time tested in these experiments. The 80 mA, 250 ms pulse setting illustrated the behaviour of CNT cathodes near the end of their useable lifetime. After a prolonged time of stable operation at low and high currents, the degradation rate exponentially increased. This behaviour indicates that the CNTs began to rapidly degrade due to a combination of heavy use and high current demand.

The impact of these results show that, using these CNT cathodes, a breast tomosynthesis system averaging 30 patients a day could run far beyond the experimentally tested lifetime of one to two years. In addition, the cathodes are capable of imaging at higher currents than typical breast tomosynthesis may require, with shorter pulse widths. Specifically the 78 mA, 125 ms setting could reduce imaging time by about two seconds compared to typical settings used by the s-DBT prototype, which typically images with 250 ms pulses. Each second decrease in imaging time decreases the chance that patient motion will negatively impact imaging quality.

Not only was typical tomosynthesis operation stably demonstrated in accelerated lifetime tests, but the feasibility of using these cathodes for 2D radiography within 4 seconds was illustrated. The CNT cathodes can produce enough current over a 4 s pulse to equal the anode exposure typically used for 2D mammography imaging. However, 4 seconds is much longer than the current imaging time for 2D mammography. For practical use, this time would need to lower to at least 1 second, which could only be achieved by increasing anode current to 50 mA, assuming a 50 mAs anode exposure. That would require at least 83 mA of cathode current for a full second, a setting which has not yet been tested with these cathodes. In addition, 50 mA current at 40 kVp would generate 2,000 W of power on the anode which could be detrimental, requiring further study. Adding 2D functionality would expand the prototype s-DBT systems' clinical appeal for imaging and intervention applications.

Finally, the degradation of a prototype s-DBT system using these CNT cathodes was tracked over several years. Among all 31 cathodes, there was an average increase of 400 V over two years, during which the system was heavily used and continues to be used to this day. The transmission rate data taken two years apart were consistent, taking into account the standard deviation among all 31 beams. This indicates a constant correlation between cathode current produced and usable anode current for X-ray production over time. In addition, the constant transmission rate indicates that there was no failure or significant change in the extraction gate mesh or any other part of the electrode assembly. Over the lifetime of the prototype s-DBT system, both cathode performance and transmission rate were found to be stable and consistent.

These CNT cathodes have shown stability and robustness for the task of digital breast tomosynthesis imaging as shown by their stability under high-current, accelerated lifetime testing; their ability to run at high power on the order of seconds; and more than two-years of reliable operation performing breast imaging tasks.

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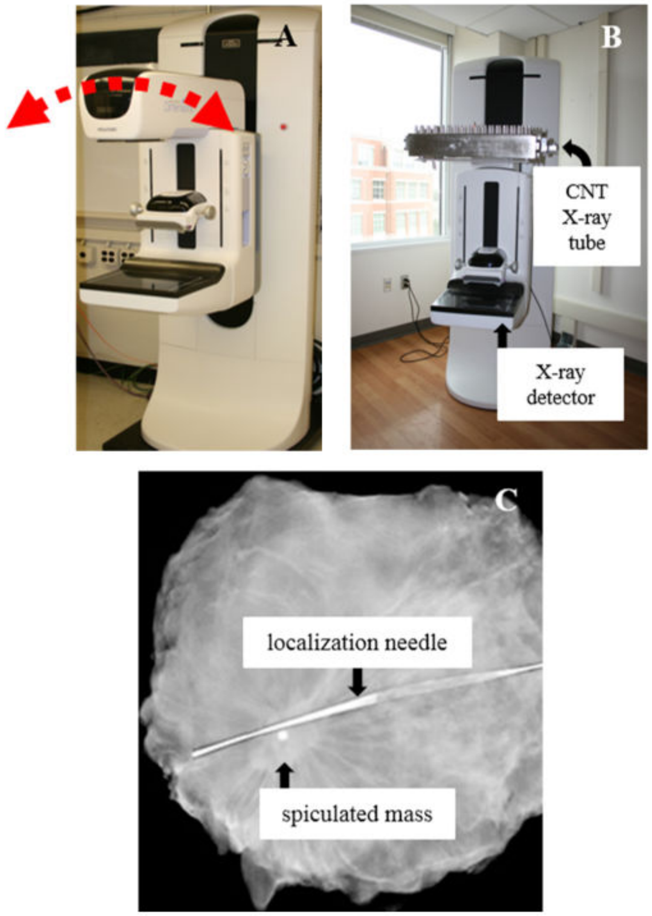

Figure 1.
(A) Hologic Selenia Dimensions (Hologic, Inc., Bedford, MA 01730) DBT system, which was adapted to build the s-DBT prototype system. The dotted arrow indicates the motion path the Hologic systems' X-ray tube takes during tomosynthesis imaging. (B) The s-DBT X-ray tube mounted on the Selenia Dimensions gantry at the N.C. Cancer Hospital. (C) Reconstructed X-ray image of a breast lumpectomy specimen acquired with the s-DBT prototype system. A spiculated mass is visible, marked by a localization needle.

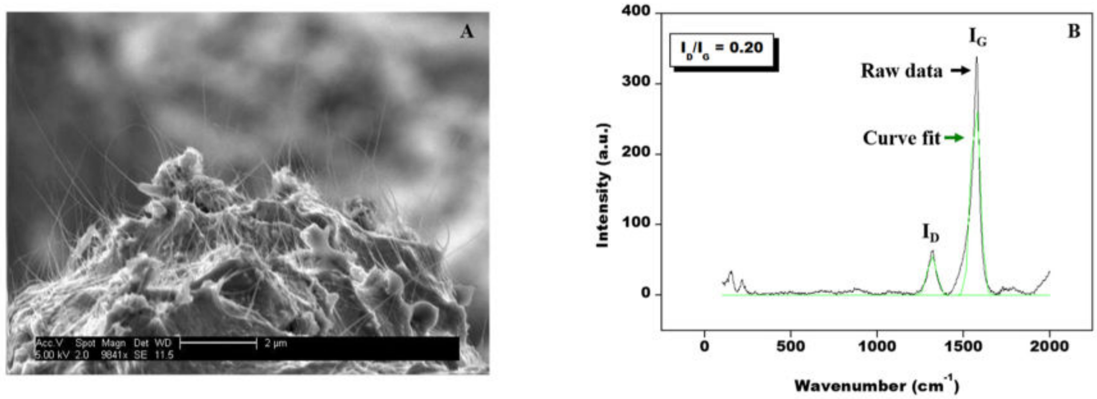

Figure 2.

(A) SEM image of a CNT cathode typical of those studied in this paper. (B) Raman spectroscopy data of a CNT sample representative of those deposited on the cathodes tested throughout this study.

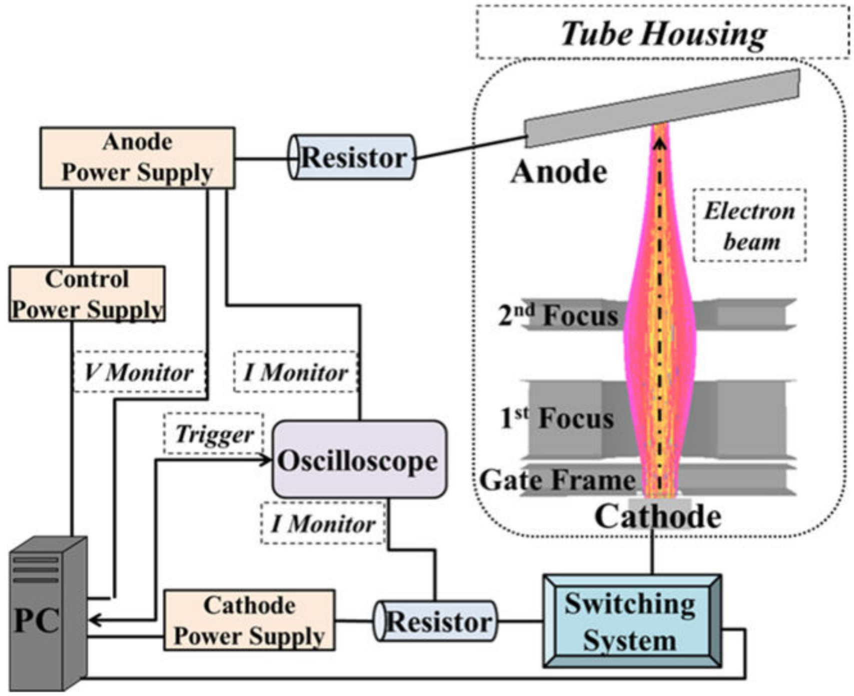

Figure 3.

Schematic of an example testing chamber setup. One cathode – anode pair is illustrated below the label "Tube Housing"; not drawn to scale with respect to the vacuum chamber or laboratory equipment.

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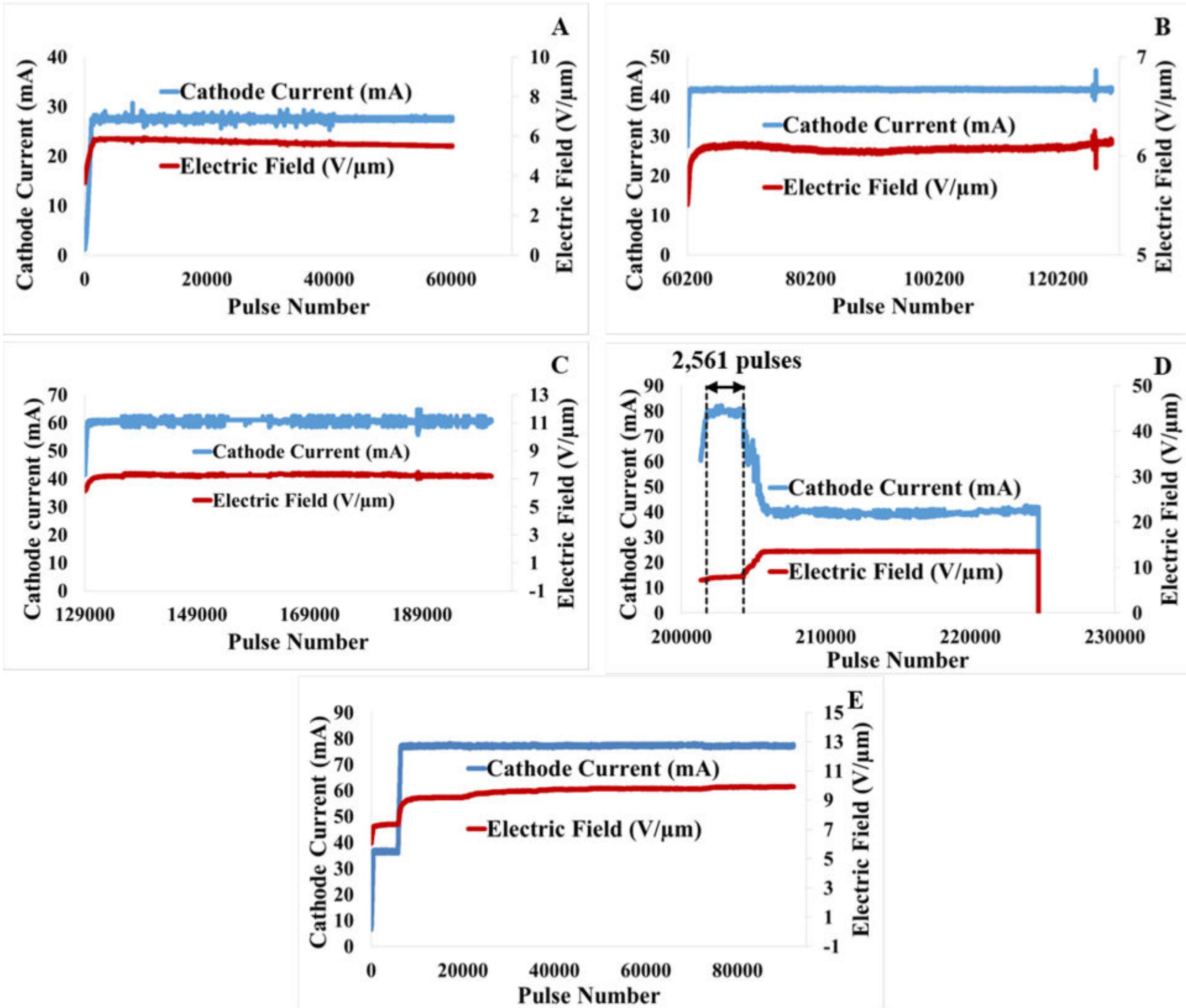

Figure 4.

Plots of cathode current and electric field data during field emission testing with 0.1 Hz frequency. Cathode current settings were (A) 27 mA, (B) 41 mA, (C) 60 mA, (D) 80 mA, and (E) 78 mA. The experimental data for (A) through (D) was gathered sequentially on a single cathode using 250 ms pulse widths. The experimental data in (E) was performed with use of a second cathode and 125 ms pulse widths.

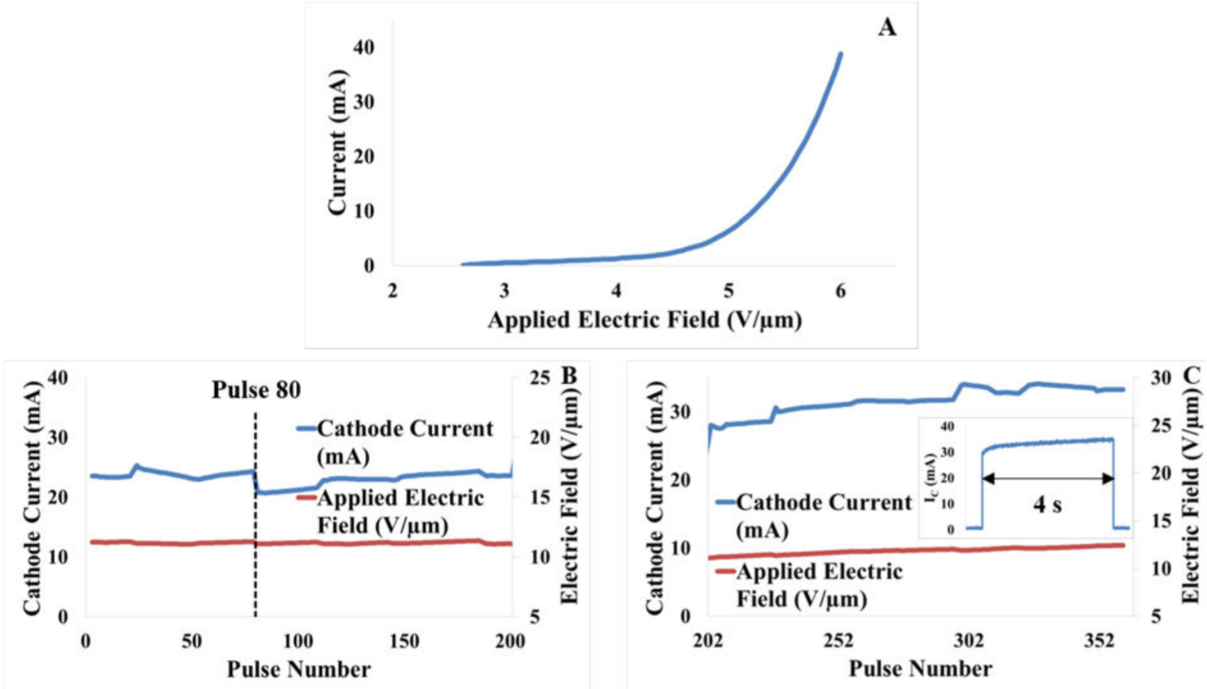

Figure 5.

Field emission results with 4 s pulses. (A) Initial I-V curve of cathode used for testing. (B) Plots of cathode current and applied electric field for the 50 mAs test. (C) Plots of cathode current and applied electric field for the 75 mAs test. (C) Inset: Sample cathode current pulse shape, 4 seconds in duration; the pulse delivered 74 mAs to anode.

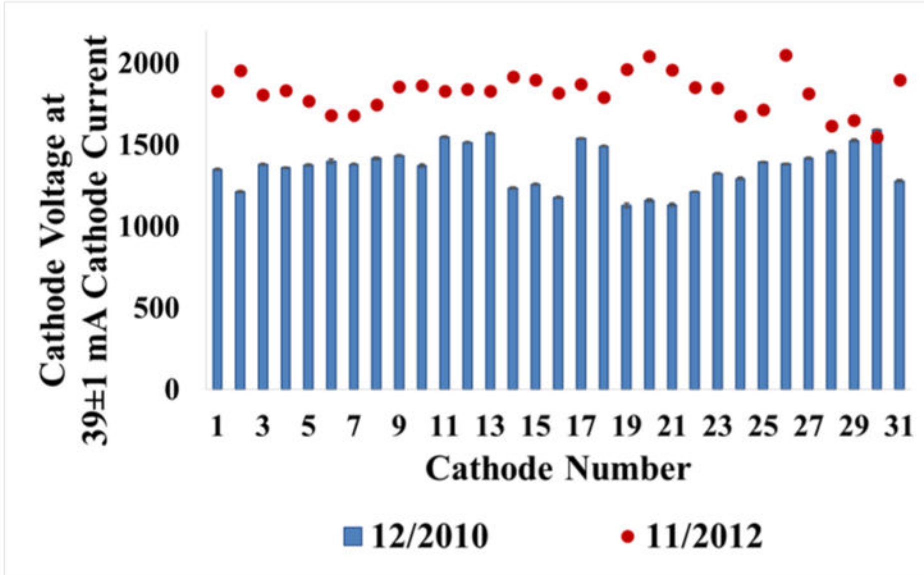

Figure 6.

Cathode voltages required to produce approximately 39 mA of cathode current, for each of the 31 cathodes in the s-DBT system, at two different time points measured in Dec. 2010 and Nov. 2012. This data demonstrates that all 31 CNT cathodes in a working s-DBT tube can reliably operate for several years. This data is consistent with the accelerated lifetime tests on a single CNT cathode shown in figure 4.

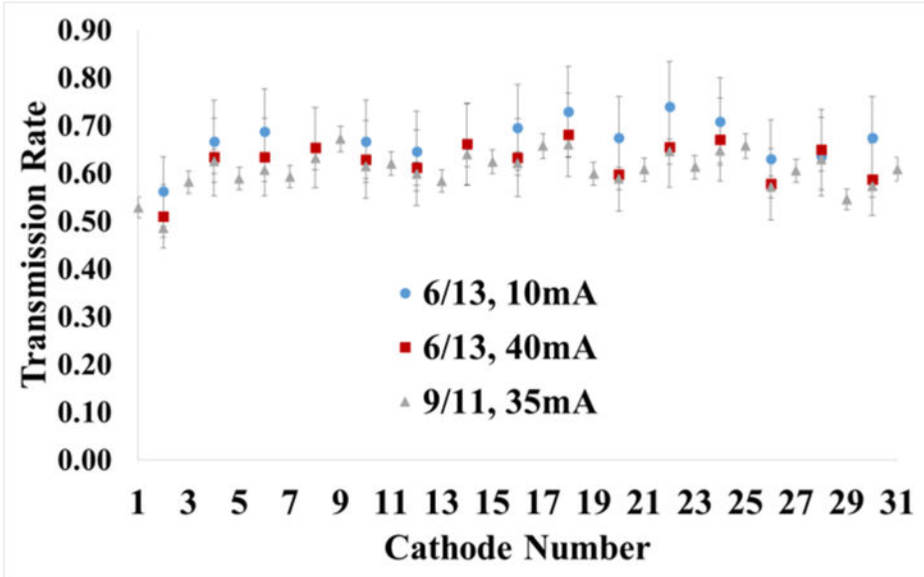

Figure 7.

Plot of the transmission rate, in fraction form, for each cathode in the s-DBT prototype X-ray tube at various times. The legend entry contains the date the data was taken in month and year followed by the set cathode current.

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Table 1

Testing summary and percent increases with respect to initial electric field.

Cathode Current (mA)	Pulse Width (ms)	Number of Pulses in Test	Total Beam-on Time (hr)	Length of Accelerated Lifetime Tested (yr) 30 patients/day	60 patients/day	Percent Change in Electric Field per 1,000 pulses (%)
27	250	59,067	4.10	1.89	0.95	0.017
41	250	40,922	2.84	1.31	0.66	0.054
60	250	71,921	4.99	2.31	1.15	0.159
80	250	2,561	0.18	0.08	0.04	3.4
78	125	85,786	2.98	2.75	1.37	0.207

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Table 2

Transmission rate data summary.

Date (Month/Year)	Anode Voltage (kV)	Cathode Current (mA)	Pulse Width (ms)	Average Transmission Rate (%)	Standard Deviation (%)
6/13	30	10	250	67	4
6/13	30	40	250	63	4
9/11	15	35	295	61	4